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Diamond-Coated Versus Conventional Bits for Rotary Cutter Head Equipment

by Roy L. Campbell, Sr., G. Sam Wong

Prepared for Headquarters, U.S. Army Corps of Engineers

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Final report

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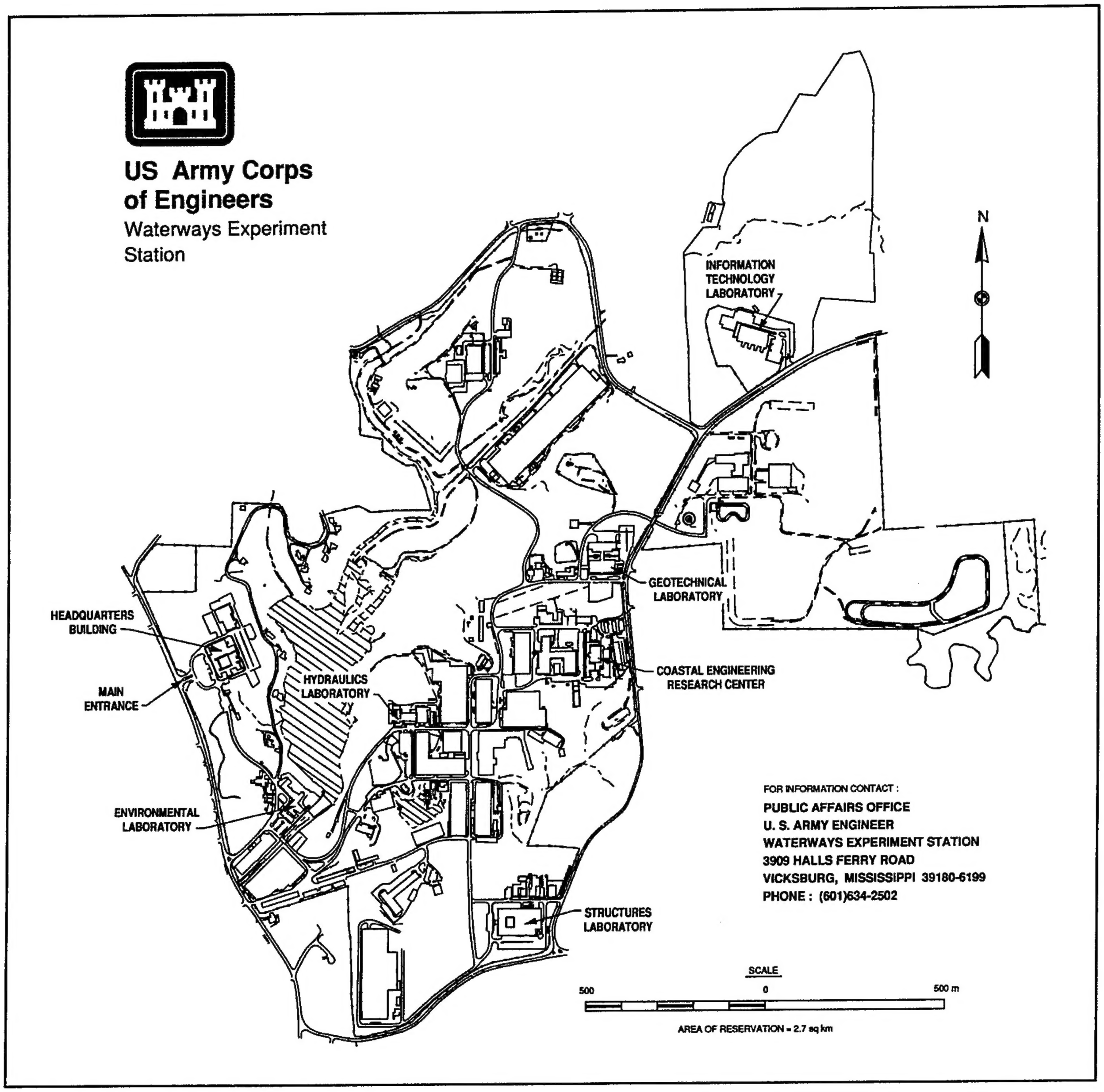

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Contents

Preface

The study described herein was authorized under Section 7 of the Water Resources Development Act of 1988, P. L. 100-676, 33 U.S.C. 2313. This work was part of the Construction Productivity Advancement Research (CPAR) Program by Headquarters, U.S. Army Corps of Engineers. The CPAR Technical Monitor for this study was Dr. Tony C. Liu (CECW-EG). Mr. David B. Mathis (CERD-C) was the CPAR Program Manager, and Mr. William F. McCleese was the U.S. Army Engineer Waterways Experiment Station (WES) Point of Contact.

Mr. Roy L. Campbell, Sr., was the WES Principal Investigator, and Mr. Wilhelm J. Kolgermann was the Principal Investigator for Alpine Equipment Corporation, as designated in the Cooperative Research and Development Agreement under the CPAR Program between the U.S. Army Corps of Engineers and private industry partner, Alpine Equipment Corporation. The study was conducted under the general supervision of Mr. McCleese, Acting Chief, Concrete Technology Division, SL, and Mr. Bryant Mather, Director, SL,

Dr. Robert W. Whalin was Director of WES. COL Bruce K. Howard, EN, was Commander.

1 Introduction

Background

Most mechanical excavation of minerals, rock, and concrete is performed by tungsten-carbide tools. The tungsten-carbide working surfaces provide approximately 100 times greater wear resistance than alloyed steel surfaces (Kolgermann 1993).

Toolmakers are presently investigating diamond films and coatings. The focus of these efforts is to improve performances and life spans of tools used for excavation by capitalizing on the diamond's unsurpassed hardness and heat conduction and its low coefficients of thermal expansion and friction.

The thin diamond films promise more complex tools with longer life spans (Schroeder 1992). These films are created through a process called chemical vapor deposition. In the process, carbon atoms are separated from methane gas molecules by heating. The carbon atoms bond with the diamond crystals upon contact. Eventually, the diamond crystals fuse into a continuous film.

Diamond tools manufactured today have tungsten-carbide inserts in which diamond powders have been bonded to the working surface of the insert with cobalt (Schroeder 1992). Diamond-coated chamfered blanks and round-nosed inserts have high impact resistance (Kolgermann 1993). The major limitation for the diamond-coated blanks and inserts is the relatively low heat resistance (700 °C; 1,300 °F) of the diamond coating. The thickness of the coating is in the range of 0.3 to 1.0 mm (0.012 to 0.039 in.).

Diamond tools are being successfully used for rotary drilling in the petroleum and mining industries. The rotary diamond-coated drill bits operated with water flushing have shown 80 to 600 times longer life than tungsten-carbide drill bits (Kolgermann 1993).

The Alpine Equipment Corporation in cooperation with major manufacturers developed drag-type cutter bits containing diamond-coated inserts (Kolgermann 1993). During factory cutting tests in both concrete and rock, the diamond-coated inserts showed excellent resistance against wear and impact and a

much longer tool life than conventional carbide inserts. Inserts were cooled during tests using water jets with a relatively high water pressure of 69 bar (1,000 psi).

Alpine estimated that mass-produced bits with diamond-coated inserts would cost about 10 times more than the conventional bits with tungsten-carbide inserts and felt that its diamond bits would have a more than 10 times longer life than tungsten-carbide bits for cutting of concrete. To investigate the feasibility of the diamond bit, Alpine entered into a Cooperative Research and Development Agreement (CRADA) with the U.S. Army Engineer Waterways Experiment Station (WES) under the Construction Productivity Advancement Research (CPAR) Program.

Objectives of Research

The objectives of this research were (a) to quantitatively demonstrate the diamond-coated-bit, cutter-boom tool as an expedient, cost-effective, concrete-removal method for the rehabilitation of locks, dams, tunnels, and other similar structures and (b) to provide real production and cost data for comparison with other removal methods. The end product of this research was to be a new diamond-coated-bit, cutter-boom tool that would give U.S. contractors a competitive edge in the world concrete-removal market.

Research Approach

Research work conducted under CPAR would use the expertise of WES in concrete mixture design and testing and the expertise of Alpine in the design and fabrication of rotary cutter head equipment. The goal of this research was to determine:

a. Magnitude of improvements in productivity of the diamond-coated bits over conventional tungsten-carbide bits.

b. Effects of coarse aggregate types and sizes and concrete strengths on productivity.

c. Extent of damage (microcracking), if any, to the concrete that remained.

d. Magnitude of noise, dust, and vibration produced by removal method.

e. Cost effectiveness of the diamond-coated bit over the conventional tungsten-carbide bit.

The productivity and levels of noise, dust, and vibration were to be determined from tests conducted both at Alpine's facility and at a Corps project. The Corps project would preferably be one in which rehabilitation work was

impending for a mass concrete structure. The effects of aggregate and concrete properties and damage resulting from removal were to be determined from tests conducted at Alpine's facility. The removal costs would be determined from tests conducted at the Corps project.

2 Mass-Concrete Test Specimens

Concrete-Mixture Proportioins

Four mixtures were proportioned for mass concrete test specimens at Alpine's facility. Aggregates and concrete proportions for these mixtures were selected to evaluate the effects of aggregate types and sizes and concrete strengths on removal rates. Mixture 1 was proportioned with a chert coarse aggregate that was highly abrasive and tough. The baseline mixture, mixture 2, was proportioned with a less abrasive and less tough, limestone coarse aggregate. Mixture 3 was a nominal 100-mm (4-in.) maximum size aggregate for comparison with mixture 2, which was proportioned with a nominal 50-mm (2-in.) maximum size aggregate. Mixture 4 was proportioned for a 28-day, 55.2-MPa (8,000-psi) compressive strength for comparison with mixture 2, which was proportioned for a 28-day, 28-MPa (4,000-psi) compressive strength. The proportions for these mixtures are summarized in Table 1.

Aggregate Properties

Aggregates were tested in unconfined compression (American Society for Testing and Materials (ASTM) D 2938) using core specimens taken from the largest size aggregate for both the chert from Mississippi and the limestone from Pennsylvania. Core specimens had a length-to-diameter ratio of approximately two and were tested in laboratory-air-dry moisture condition at a rate of loading of 22.2 N/sec (5 lb/sec) for chert and 8.9 N/sec (2 lb/sec) for limestone. The mean test time was 22.6 min for chert and 14.9 min for limestone specimens.

The mean value for compressive strength (Table 2) was 519 MPa (75,200 psi) for the chert and 79 MPa (11,500 psi) for the limestone. The mean value for modulus of elasticity (Table 2) was 136,000 MPa (19,700,000 psi) for the chert and 32,900 MPa (4,780,000 psi) for the limestone.

Table 1
Summary of Concrete-Mixture Proportions

Item	Mixture 1	Mixture 2	Mixture 3	Mixture 4
Cement kg/m^3 (lb/yd^3)	297 (500)	227 (383)	214 (360)	344 (579)
Coarse aggregate kg/m^3 (lb/yd^3)	725 (1,222)	664 (1,119)	1,553 (2,617)	994 (1,675)
Fine aggregate kg/m^3 (lb/yd^3)	1,156 (1,947)	1,400 (2,359)	553 (932)	475 (800)
Air-entraining admixture mL/m^3 (fl. oz/yd^3)	503 (13)	310 (8)	232 (6)	348 (9)
Water-reducing admixture mL/m^3 (fl. oz/yd^3)	0	735 (19)	0	3,096 (80)
Water-cement ratio, by mass	0.42	0.51	0.50	0.35

The mean value for unconfined compressive strength was approximately six and a half times higher for the chert aggregate than for the limestone aggregate. The mean value for modulus of elasticity was approximately four times higher for the chert aggregate than for the limestone aggregate. The variances in specimen results for both aggregates were significant indicating variations in the aggregate material and test procedures. Project limitations prevented the determination of how much variation was the result of each. However, for our purpose, these mean values are representative.

The chert and limestone aggregates were tested for abrasion loss in accordance with ASTM C 535. Results of tests showed the loss for the chert aggregate was approximately 37 percent less than that for the limestone aggregate. The abrasion loss was 20.8 percent for the chert aggregate and 33.2 percent for the limestone aggregate (Table 3).

The aggregate abrasion loss for the chert was approximately 37 percent less than that for the limestone. Results for abrasion loss tests (ASTM C 535) showed a 20.8-percent loss in mass for the chert aggregate and a 33.2-percent loss in mass for the limestone aggregate (Table 3).

Table 2
Unconfined Compressive Strength Test Results: Coarse Aggregates

Limestone Aggregate from Pennsylvania			Chert Aggregate from Mississippi		
Specimen	Compressive Strength MPa (psi)	Modulus of Elasticity 10^3 MPa (10^6 psi)	Specimen	Compressive Strength MPa (psi)	Modulus of Elasticity 10^3 MPa (10^6 psi)
L-1	54.0 (7,840)	25.2 (3.66)	C-1	292 (42,300)	170 (24.6)
L-2	46.9 (6,810)	3.79 (0.549)	C-2	851 (123,000)	229 (33.3)
L-3	88.8 (12,900)	9.87 (1.43)	C-3	323 (46,900)	153 (22.2)
L-4	83.4 (12,100)	64.9 (9.41)	C-4	396 (57,500)	149 (21.6)
L-5	83.4 (12,100)	1.37 (0.199)	C-5	1,180 (171,000)	219 (31.8)
L-6	63.6 (9,220)	9.25 (1.342)	C-6	714 (104,000)	85.5 (12.4)
L-7	68.6 (9,940)	178 (25.8)	C-7	74.2 (10,800)	33.2 (4.82)
L-8	44.6 (6,470)	1.35 (0.195)	C-8	287 (41,600)	63.5 (9.21)
L-9	46.0 (6,670)	23.3 .(3.38)	C-9	256 (37,100)	101 (14.7)
L-10	72.3 (10,500)	21.5 (3.12)	C-10	851 (123,000)	118 (17.1)
L-11	131.0 (19,000)	16.1 (2.34)	C-11	130 (18,900)	49.0 (7.11)
L-12	94.0 (13,600)	81.5 (11.8)	C-12	872 (127,000)	256 (37.1)
L-13	79.6 (11,500)	9.34 (1.35)			
L-14	155 (22,400)	15.6 (2.26)			
Mean	79.3 (11,500)	32.9 (4.78)	Mean	519 (75,200)	136 (19.7)
Range	44.6-155 (6,470-22,400)	1.35-178 (0.195-25.8)	Range	74.2-1,180 (10,800-171,000)	33.2-256 (4.82-37.1)
Std. Dev.	31.7 (4,600)	47.8 (6.94)	Std. Dev.	356 (51,600)	73.2 (10.6)
Coef. of Var.	40.0%	145.3%	Coef. of Var.	68.6%	54.0%

Table 3 Abrasion Loss Test Results for Coarse Aggregates		
Aggregate	**Size (ASTM C 33) No.**	**Abrasion Loss (ASTM C 535) %**
	1	32.3
	3	31.7
	57	35.7
Pennsylvania Limestone	mean	33.2
Mississippi Chert	467	20.8

Concrete Properties

The mean test results for concrete mixture design 1 containing the Mississippi chert aggregate showed a 28-day compressive strength of 20.8 MPa (3,010 psi) for cast cylinder specimens (ASTM C 39) and 20.3 MPa(2,940 psi) for the core specimens (ASTM C 42). The mean test results for concrete mixture design 2 containing 51-mm (2-in.) Pennsylvania limestone aggregate showed a 28-day compressive strength of 24.3 MPa (3,530 psi) for cast cylinder specimens (ASTM C 39) and 23.0 MPa (3,340 psi) for the core specimens (ASTM C 42). The mean compressive strengths for cores were less than those for cast specimens due to field curing at low ambient temperatures. These results are presented in Table 4.

The splitting tensile strength and modulus of elasticity test results (ASTM C 42) were from core specimens only. The mean splitting tensile results (Table 4) for mixture 1 were slightly higher than that for mixture 2. The mean modulus of elasticity test results (Table 4) were lower for mixture 1 than for mixture 2.

The abrasion loss test results for concrete (Table 4) were from tests of specimens cast at the batch plant. The concrete abrasion loss (ASTM C 1138) for chert concrete mixture was approximately 31 percent less than that for the limestone.

The concrete for test stand 1 had an estimated 28-day design strength in compression of 13.8 (2,000 psi) and a 19-mm (3/4-in.) nominal maximum size aggregate.

Table 4
Summary of Concrete Test Results

Concrete Mixture Design		1	2	3	4
Mass Concrete Test Specimens		1 and 4	2 and 3	*	*
Coarse Aggregate		38-mm (1-1/2-in.) Chert	51-mm (2-in.) Limestone	51-mm (2-in.) Limestone	102-mm (4-in.) Limestone
Cast Specimens	Compressive Strength, ASTM C 39 MPa (psi)	20.8 (3,010)	24.3 (3,530)	*	*
	Abrasion Loss, ASTM C 1138 10^{-6} m^3 (10^{-6} yd^3)	540 (706)	782 (1,020)	*	*
Core Specimens (ASTM C 42)	Compressive Strength MPa (psi)	20.3 (2,940)	23.0 (3,340)	*	*
	Splitting Tensile Strength MPa (psi)	1.68 (244)	1.65 (239)	*	*
	Modulus of Elasticity 10^4 MPa (10^6 psi)	1.09 (1.58)	1.28 (1.85)	*	*

* Research effort discontinued before test was performed.

3 Rotary Cutter Head Equipment

Cutter Bits

Both conventional and diamond-coated bits were tested. The conventional bits were 64-mm- (2-1/2-in.-) gage, conical rotating bits having a 19-mm- (3/4-in.-) diameter insert. The diamond-coated bits (Figure 1) were the same as the conventional bits except the tip of the insert was coated with several layers of fine diamonds.

Single-Drum Cutter Head

The cutter head equipment initially used to evaluate removal rates consisted of a seven-bit, single-drum cutter head (Figure 2). The hydraulic drum motor was powered by a 105-hp electro-hydraulic power pack. The horsepower of the motor is dependent on the cutter drum speed, hydraulic flow rate, and operating pressure of the system. At 80-percent system efficiency, the flow per revolution of the cutter drum would be 0.93 L (0.25 gal), and the hydraulic pressure would be approximately 207 bar (3,000 psi). Due to concerns that the diamond coatings would debond as a result of the excessive heat generated by the high bit speeds, each bit tip was cooled by an individual water jet in addition to the standard water spray directed at the bits. Equipment details can be found in Appendix A.

Twin-Drum Cutter Head

The twin-drum equipment used to remove concrete from mass concrete test specimens had previously been used for boring and tunnelling work at the Super-Collider project in Texas. The twin-drum cutter head (Figure 3) contained a total of 90 bits. The hydraulic drum motor that drove the twin drums was powered by a 165-hp electro-hydraulic power pack. Normally, cuts are made primarily by the leading drum in the direction of the boom swing and by

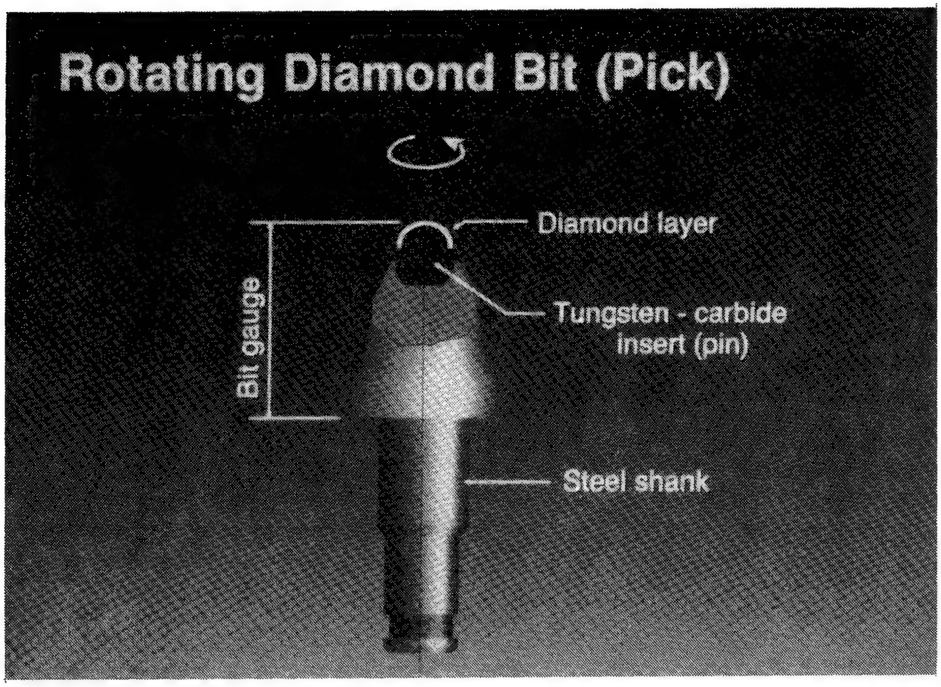

Figure 1. Diamond-coated bit

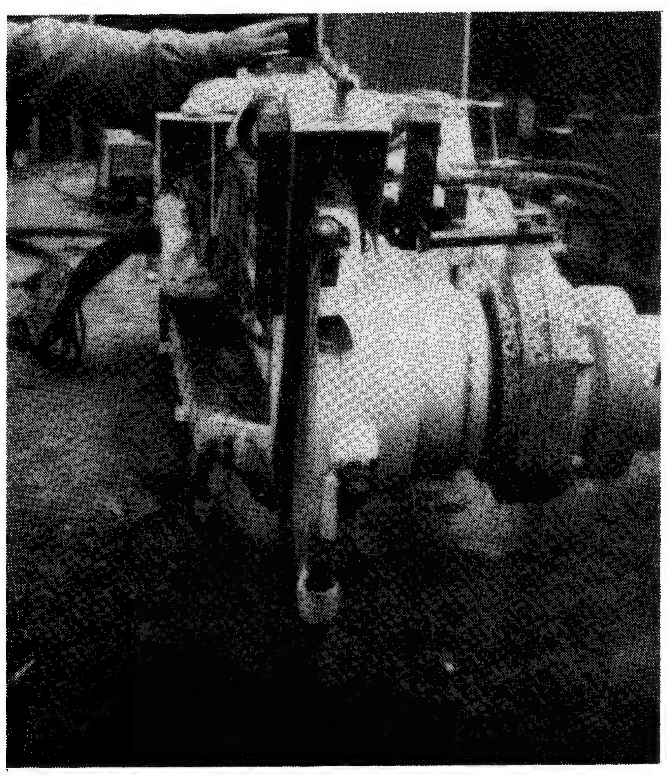

Figure 2. Single-drum rotary head cutter

the other drum when the boom swing is reversed. However, to reduce cost, only the right drum was equipped with test bits, and cuts were made by swinging the boom from left to right. Worn-out conventional bits were installed on the unused left drum to protect it from damage. The tips of the worn-out bits were cut off so they would not contact the concrete during removal. Equipment details can be found in Appendix B.

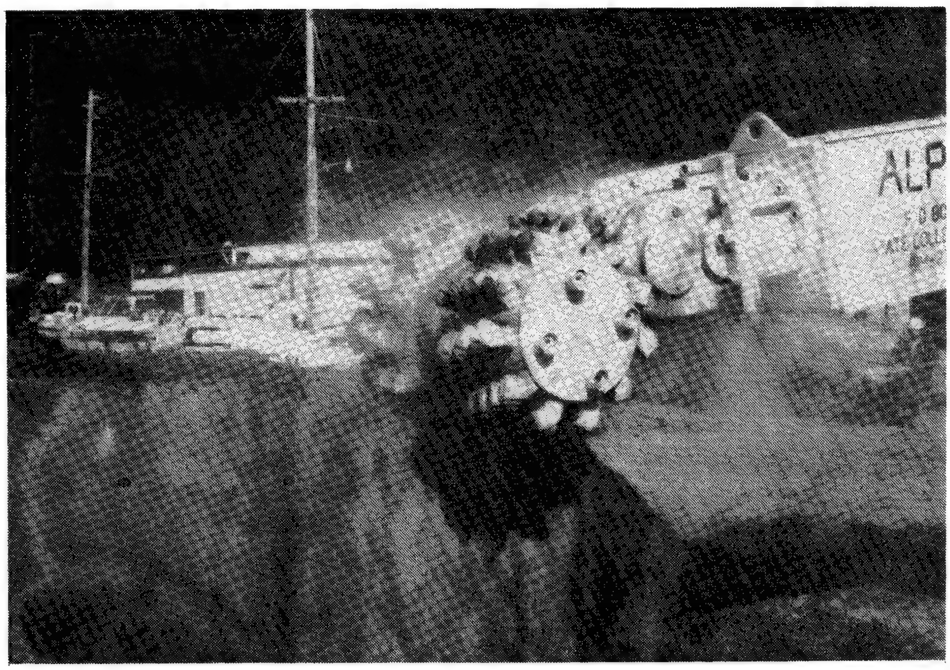

Figure 3. Twin-drum rotary cutter head

4 Concrete-Removal Test Results

Test stand 1 (Figure 4) contained four 1.2-m-wide by 1.2-m-high by 2.4-m-long (4-ft-wide by 4-ft-high by 8-ft-long) mass concrete test specimens. The first and fourth specimens in the test stand contained mixture 1 concrete; the second and third specimens, mixture 2. The test stand concrete that separated the mass concrete test specimens was also removed, and the rates were recorded.

Microcracking

The petrography report detailing the extent of removal-induced microcracking resulting from the use of rotary cutter heads is presented in Appendix C.

Single-drum cutter head

The petrographic analysis of concrete cores from mass concrete test specimen 1 containing chert as the coarse aggregate showed that microcracking remained in the concrete surface as a result of removal for both the diamond-coated and the conventional tungsten-carbide bits. Fractures were observed as deep as 25.4 mm (1 in.) and through the coarse aggregates as well as the paste.

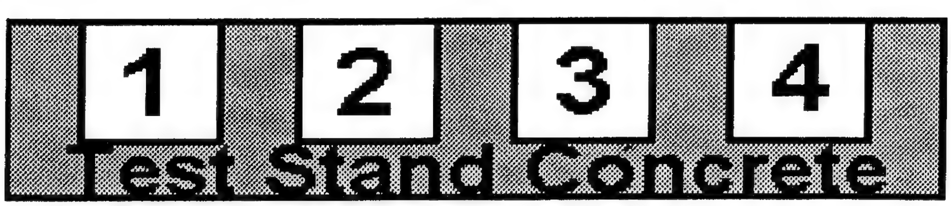

Figure 4. Locations of mass concrete test specimens within test stand 1

Twin-drum cutter head

The petrographic analysis of concrete cores from mass concrete test specimen 2 containing limestone as the coarse aggregate showed that microcracking remained in the concrete surface as a result of removal for both the diamond-coated and the conventional tungsten-carbide bits. Fractures were observed as deep as 25.4 mm (1 in.) and through the coarse aggregates as well as the paste.

Removal Rates

Preliminary removal tests were performed to evaluate equipment readiness and to finalize test plans. The seven-bit cutter head shown in Figure 2 was used to remove concrete from mass concrete test specimen 1 containing chert aggregate. The drum was operated to produce an approximate bit speed of 7.3 m/sec (24 ft/sec). Results of performance tests (Table 5) showed that the conventional carbide bits removed concrete at the rate of 1.1 m^3/hr (1.4 yd^3/hr) and the diamond-coated, at 0.9 m^3/hr (1.2 yd^3/hr). Removal rates were computed using actual cutting times which excluded all other times such as repositioning cutter head, moving equipment, performing equipment maintenance, and inspecting bits for wear.

Table 5
Properties of Concretes and Removal Rates for Single-Drum Cutter

Mix No.	Aggregate Type	Nominal Maximum Size Aggregate mm (in.)	Compressive Strength MPa (psi)	Bit Speed m/sec (ft/sec)	Removal Rate Based on Cutting Times Only m^3/hr (yd^3/hr)	
					Diamond-Coated Bits	Tungsten-Carbide Bits
1	Chert	38 (1-1/2)	21 (3,000)	7.3 (24)	0.9 (1.2)	1.1 (1.4)

For the twin-drum cutter head (Figure 3), the diamond-coated bits had lower removal rates than the conventional bits with the exception of removal from test stand concrete. The removal of concrete began with mass concrete specimen 2. The first half of the specimen was removed using diamond-coated bits in which the removal rate was 2.8 m^3/hr (3.6 yd^3/hr). Modifications were made to the hydraulic system; however, the previous operating parameters including bit speed for the diamond-coated bits were not furnished to WES by Alpine. All remaining removal was made using an approximate bit speed of 3.0 m/sec (9.7 ft/sec). Removal rates for the twin-drum cutter head are summarized in Table 6.

Table 6
Properties of Concretes and Removal Rates for Twin-Drum Cutter

Mix No.	Aggregate Type	Nominal Maximum Size Aggregate mm (in.)	Compressive Strength MPa (psi)	Bit Speed m/sec (ft/sec)	Removal Rate Based on Cutting Times Only m^3/hr (yd^3/hr)	
					Diamond-Coated Bits	Tungsten-Carbide Bits
1	Chert	38 (1-1/2)	21 (3,000)	3.0 (9.7)	11.1 (14.5)	12.1 (15.8)
2	Limestone	51 (2)	24 (3,500)	#	2.8 (3.6)	*
				3.0 (9.7)	*	13.5 (17.7)
Test stand	Limestone	19 (3/4)	14 (2,000)	3.0 (9.7)	22.4 (29.3)	16.7 (21.9)
3	Limestone	51 (2)	*	*	*	*
4	Limestone	102 (4)	*	*	*	

Information was not furnished to WES by Alpine (modifications were made to hydraulic after removal of half of mass concrete specimen 2).
* Research effort discontinued before test was performed.

Bit Life

Concrete-removal tests were initially performed using the single-drum cutter head shown in Figure 2. Results of the tests showed that the shanks for both diamond-coated and conventional bits had excessive wear as a result of the concrete removal. The outer bits and bit holders (Figure 5) were the most worn because the freshly cut concrete face ahead of the boom sweep abraded the shank and holder sides. It appeared that shanks would wear down to the point that inserts would be lost before bit life could be determined. It was concluded that bit life could not be determined using the seven-bit cutter head; therefore, the remaining removal would be performed using the 90-bit, twin-drum cutter head shown in Figure 3.

Results of tests using the twin-drum cutter head showed that the shanks for both the diamond-coated (Figure 6) and the conventional bits had excessive wear as a result of the concrete removal. Extreme wear of the shank of one bit resulted in the loss of the bit insert (Figure 7). Some damage to the diamond coatings was observed and was due to impact (Figure 8). Again, it appeared that shanks would wear down to the point that inserts would be lost before bit life could be determined.

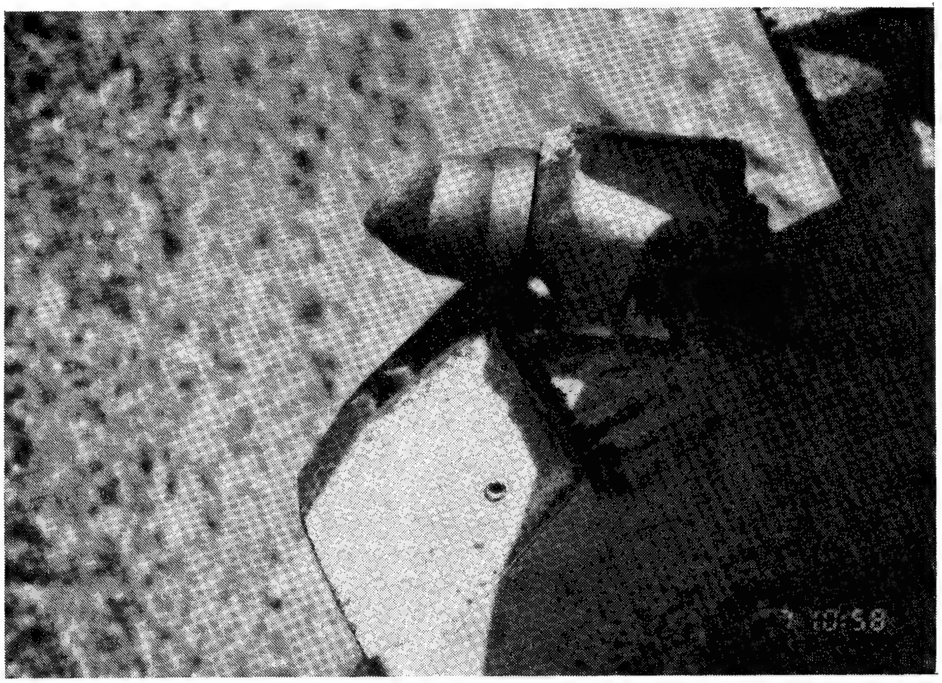

Figure 5. Abrasion wear to bit shank and holder

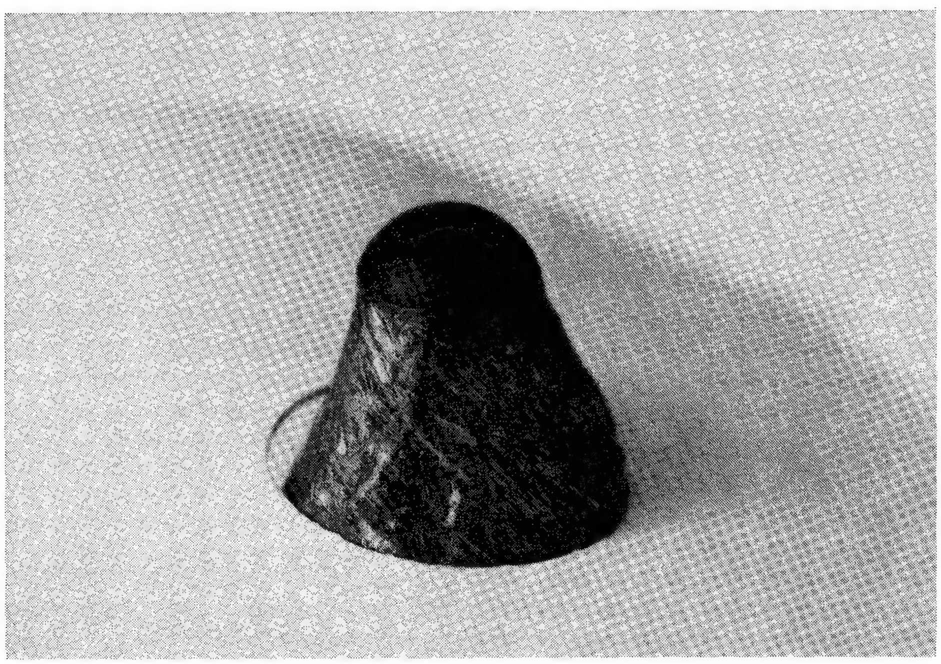

Figure 6. Excessive wear to shank of diamond-coated bit

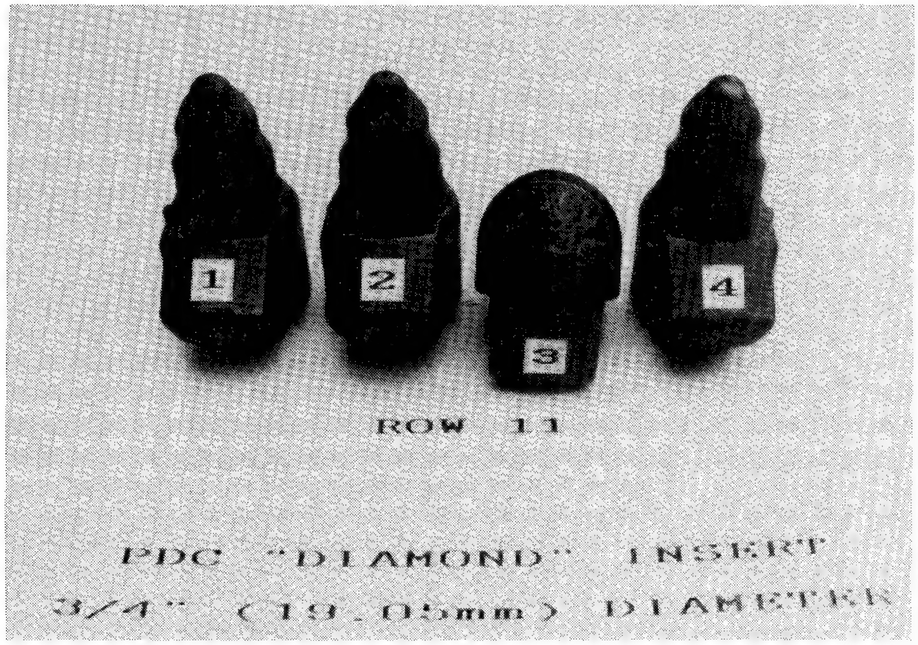

Figure 7. Bit No. 3 lost due to extreme bit-shank wear

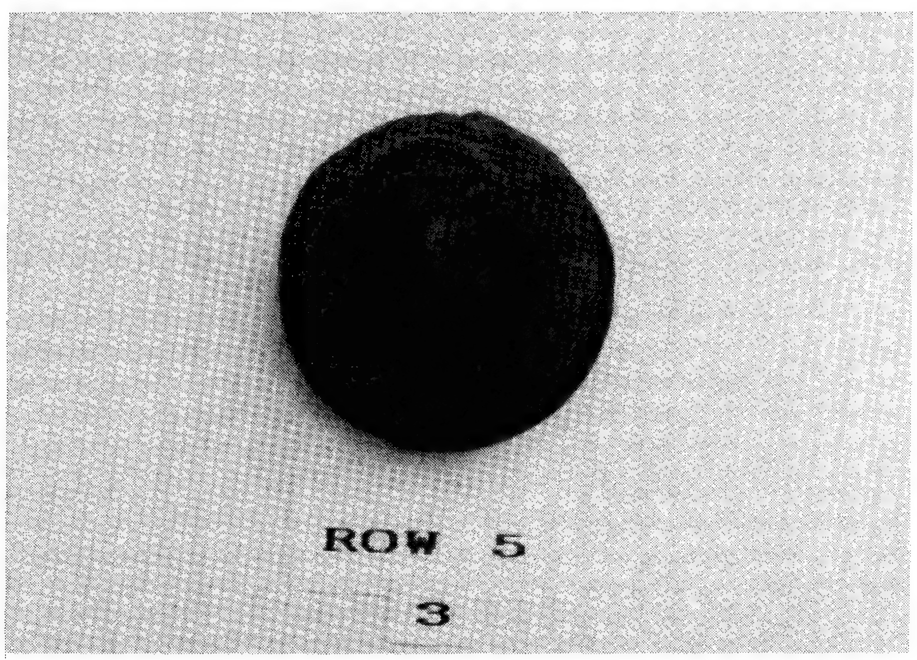

Figure 8. Indention in diamond coating due to impact

Bit-shank and holder-side wear was accelerated to some degree as a result of the abrasion-resistant coarse aggregates used, especially the Mississippi chert aggregate. Tests were discontinued because the cost of hardening the shanks would make the diamond-coated bit too expensive to market commercially.

Safety

Vibration

Ground vibrations generated by operation of the rotary cutter head equipment were evident by the ripples observed in the water puddles located within 3.05 m (10 ft) of the mass concrete test specimens. The magnitude of these vibrations was not measured because the project was discontinued before measurements were scheduled to be made.

Noise

Noise levels generated by operation of the rotary cutter head equipment were high enough that those working on or around the equipment needed to wear hearing protection in the form of ear plugs. The magnitude of noise was not measured because the project was discontinued before measurements were scheduled to be made.

Dust

Some dust was generated by operation of the rotary cutter head equipment, even though a constant spray of water was directed at the cutting surface. In the field, any workmen immediately downwind of the removal would have to be provided with protection against this airborne dust. The level of airborne dust was not measured because the project was discontinued before measurements were scheduled to be made.

5 Discussion

The Corps of Engineers has been involved with a number of repair projects where unexpectedly sound concrete was encountered by the contractor. Three of these projects involved removal using rotary cutter heads (John Day Dam, Little Goose Dam, and Mississippi River Lock No. 20). Claims for compensation by the contractors were made under the "differing site condition" clause of the rehabilitation contracts and were based on the strength of the concrete being higher than expected, coarse aggregate being too tough and abrasion-resistant, coarse aggregate being larger than expected, or a combination of these.

There were some concerns as to what extent microcracking occurs as a result of using the rotary cutter head. Also of concern were the magnitudes of vibration generated by the cutter head at various distances from the point of removal. During a visit to Joliet Channel Wall repair project in 1985, investigators observed that the rotary cutter head generated strong vibrations that could be felt in abutting monoliths during concrete removal. Therefore, it was important that the CPAR study include the above parameters in evaluating the performances of both the diamond-coated and conventional bits.

Test results showed that the conventional bits had slightly higher concrete removal rates than diamond-coated bits with the exception of the time when the rotary head cutter was used to remove the test stand concrete. Analysis of core specimens showed that microcracking was present in the concrete surfaces that remained after removal.

In general, the diamond-coated bits appeared to have less wear, with the exception of a few bits in which the coatings had been damaged by impact. The use of the abrasion-resistant aggregate from Mississippi accelerated wear of the bit inserts and shanks. This aggregate is commonly used as the coarse aggregate for concrete in highway and slab construction in Mississippi and surrounding states. Chert aggregate has also been used in concretes for Corps lock and dam structures, such as Jonesville Lock and Dam.

Due to the excessive wear of the shanks, the testing was stopped. For testing to be continued, the shank would have to be hardened, which meant an unexpected expense to the research project. Even if the diamond-coated bits

did perform as Alpine expected them too, the cost of hardening the shanks would make the bits too costly to market commercially. By mutual agreement between WES and Alpine, the joint research contract was terminated.

6 Conclusions

Results of testing indicate that diamond-coated bits do not remove concrete any faster than conventional tungsten-carbide bits. The diamond-coated bit inserts appeared to wear less than the tungsten-carbide inserts but showed signs of impact damage. The estimated benefit of the diamond-coated bits having more than 10 times longer life than that of conventional bits (Kolgelmann 1993) could not be proved or disproved as testing was discontinued because of the excessive wear of bit shanks. The effects of coarse aggregate types and sizes and of concrete strengths on productivity also could not be evaluated because of incomplete test results.

The bit shanks would have to be hardened in order to benefit from the extended bit life resulting from the use of the diamond-coated inserts. The cost of hardening the bit shanks would make the diamond-coated bits too expensive to market commercially.

The impact of cutter head bits on the concrete induces microcracking in the surfaces that remain after removal. The extent of microcracking will vary depending on the size and horsepower of the cutter head system and the properties of the remaining concrete.

Ground vibration, noise, and dust are generated by the cutting operation. The magnitude of these potential safety hazards will vary depending on the rotary cutter head equipment used.

References

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a. Designation C 33. "Standard specification for concrete aggregates."

b. Designation C 39. "Standard test method for compressive strength of cylindrical concrete specimens."

c. Designation C 42. "Standard test method for obtaining and testing drilled cores and sawed beams of concrete."

d. Designation C 535. "Standard test method for resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles machine."

e. Designation C 1138. "Standard test method for abrasion resistance of concrete (underwater method)."

f. Designation D 2938. "Standard test method for unconfined compressive strength of intact rock core specimens."

Kolgelmann, W. J. (1993). "Cutting tool development: novel, high-production, low-cost concrete removal method for locks, dams, tunnels and other concrete structures," unpublished report, Alpine Equipment Corporation, State College, PA.

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Appendix A
Equipment Details for Single-Drum Rotary Head Cutter

CUTTING SYSTEM

Cutter boom style:	Telescoping "sumping" boom with a 406-mm (16-in.) stroke
Cutting principle:	Transverse "ripper" head
Cutter head diameter:	914 mm (36 in.) measured from tips of new bits
Number of bits:	7
Bit type:	Rotating, "point attack" bits
Angle of attack:	45 degrees
Bit gauge:	63.5 mm (2.5 in.)
Cutter bit inserts:	Tungsten-carbide, cone-shaped tip inserts and diamond-coated, semi-spherical tip inserts having a 19.05-mm (3/4-in.) diameter
Dust suppression and cooling of bits:	External, cone-type water sprays and water jet in front of each bit
Cutter boom drive:	Axial motor with a fixed piston displacement of 75 cm^3 (4.58 $in.^3$)
Cutter transmission:	Spiral-bevel/spur gears reduction: i = 12.432:1
Cutting speed:	0 to 177 rpm
Cutting range: Height:	3.95 m (12 ft - 11.5 in.)
Width:	5.20 m (17 ft - 1 in.)
Below tracks:	100 mm (4 in.)

CARRIER VEHICLE

Chassis model:	Alpine ABM 100-Series
Overall weight:	Approximately, 14 metric tons (31,000 lb)
Prime mover:	Electric motors 460 volts, 60 c/s (Hz)
Crawler drive:	2 x 10 hp (2 x 7.5 kW)
Pump drive:	1 x 10 hp (1 x 7.5 kW)
Conveyor drive:	2 x 10 hp (2 x 7.5 kW)
Propulsion system:	Crawler tracks
Machine stabilization:	One stabilizer shoe in rear and one front stabilizer integrated in loading apron
Machine operator:	1 person

ELECTRO-HYDRAULIC POWER PACK

Type and location:	Skid-mounted; behind cutting machine
Prime mover:	Electric motors 460 volts, 60 c/s (Hz)
Installed horsepower:	105 hp (78 kW)
Hydraulic pumps:	Axial piston, variable displacement 156 cm^3 (9.51 $in.^3$)

Appendix B
Equipment Details for Twin-Drum Rotary Head Cutter

CUTTING SYSTEM

Cutter boom style:		Full-size Alpine Model H3T long "knuckle" cutter boom
Cutting principle:		Transverse ripper" head
Cutter head diameter:		705 mm (27.75 in.) measured from tips of new bits
Number of bits:		2 x 45
Bit type:		Rotating, "point attack" bits
Angle of attack:		45 degrees
Bit gauge:		63.5 mm (2.5 in.)
Cutter inserts		Tungsten-carbide, cone-shaped tip inserts and diamond-coated, semi-spherical tip inserts having a 19.05-mm (3/4-in.) diameter
Cutter boom drive:		Axial motor with a fixed piston displacement of 250 cm^3 (15.25 $in.^3$)
Cutter transmission:		Spiral-bevel/spur gears reduction: i = 20.12:1
Cutting speed:		0 to 87 rpm
Cutting range:	Height:	6.71 m (22 ft - 0 in.)
	Width:	9.75 m (32 ft - 0 in.)
	Below tracks:	2.44 m (8 ft - 0 in.)
Dust suppression and cooling of bits:		External, cone-type water sprays

CARRIER VEHICLE

Chassis model:	Alpine ABM 300-Series
Overall weight:	Approximately, 42 metric tons (93,000 lbs) including cutter boom and electro-hydraulic power packs
Prime mover:	Electric motors 460 volts, 60 c/s
Electro-hydraulic power pack:	2 x 165 hp (2 x 123 kW)
Hydraulic system for cutter head:	Closed loop, variable displacement axial piston pump having a maximum displacement of 250 cm^3 (15.25 $in.^3$) per revolution
Propulsion system:	Caterpillar-style crawler tracks
Machine stabilization	One stabilizer shoe in rear and one front stabilizer integrated in dozer blade
Machine operator:	1 person

CONDENSED SPECIFICATIONS OF HYDRAULICALLY POWERED ALPINE CONCRETE CUTTING SYSTEM

Hydraulic Power Pack

Electric pump drive:	165 hp (123 kW), 4 pole, 460 V, 60 c\s, water cooled electric motor

Hydraulic pump	Type:	Variable displacement axial piston pump
	Displacement:	Maximum 250 cm^3 (15.25 $in.^3$) per revolution
	Operation:	Closed circuit
Specification sheet:		Rexroth RA 210/7.86 Type AA4V-Series 2
Hydraulic flow:		0 to 438 litres/min (115.6 gpm)
Peak Pressure:		up to 448 bars (6,500 psi)

Cutter Boom

Cutter head style:		Transverse "ripper"
Cutter bits:		Conical, rotating " point attack"
Bit insert:	Diameter:	19.06 mm (3/4 in.)
	Type:	Diamond-coated, semi-spherical tip inserts and tungsten-carbide, cone-shaped tip inserts
Cutter transmission:	Type:	Bevel-spur gear
	Reduction:	i= 20:1
Cutter drive:		Hydraulic
Cutter motor:		Axial-piston motor with fixed displacement of 250 cm^3 (15.25 $in.^3$) Volvo FII-250
Peak pressure:		420 bar (6,000 psi)

Appendix C
Petrographic Report: Extent of Removal-Induced Microcracking

CEWES-SC-EP (1110-2-1403b)   4 Mar 94

MEMORANDUM FOR MR. ROY CAMPBELL, CEWES-SC-CA

SUBJECT: Examination of Concrete Cores from Alpine Removal Technique

1. Samples. Four cores were received from you for examination to determine the extent of internal damage to the concrete when subjected to the Alpine removal technique. The cores were identified as 930245, 930246, 940008, and 940009. Both samples 930245 and 930246 were composed of concrete made using a siliceous aggregate. Samples 940008 and 940009 were concrete samples made using limestone coarse aggregate.

2. The following table identifies the different test conditions represented by each sample:

Table 1
Alpine Concrete Removal Samples

CTD S.N.	Description
930245	Six-in.-diameter core (Field Id: Chert 5-5-93) taken from mass concrete specimen 1 in which surface was removed by single-drum, diamond-bit cutter boom.
930246	Six-in.-diameter core (Field Id: Chert 5-6-93) taken from mass concrete specimen 1 in which surface was removed by single-drum, tungsten-carbide bit cutter boom.
940008	Six-in.-diameter core (Field Id: Limestone 10-25-93) taken from mass concrete specimen 2 in which surface was removed by twin-drum, diamond-bit cutter boom.
940009	Six-in.-diameter core (Field Id: Limestone 10-26-93) taken from mass concrete specimen 3 in which surface was removed by twin-drum, tungsten-carbide bit cutter boom.

Procedure

3. The as-received cores were examined for visual signs of damage.

4. After initial inspection, the cores were cut longitudinally using a diamond saw to minimize further damage to the specimens. Two saw cuts were produced as the slab was cut. It was then impregnated with epoxy containing a fluorescent dye. The slabs were vacuum saturated to fill cracks in the concrete. The first samples were ground to

remove the excess epoxy which tended to reveal pores as well as cracks filled with the epoxy. Later samples were cut again following epoxy impregnation to reveal only the cracks.

5. The prepared slabs were examined using an ultraviolet light, and the depth of damaged concrete was measured. Photographs were made of the samples to illustrate the nature and orientation of the cracking.

<u>Results</u>

6. An examination of as-received core surfaces indicated similar physical features on all samples. Grooves with striations where the cutter ripped through the concrete were evident. These grooves were typically 150 mm wide. The aggregate particles were generally shattered in the cutter path, but the paste was essentially intact. The chert coarse aggregate was fractured, and the broken fragments tended to be loose and easily dislodged. The fracturing of the coarse aggregate particles tended to be more severe in the concrete containing siliceous coarse aggregate (930245 and 930246) than with the limestone coarse aggregate.

7. Samples 930245 and 930246 consisted of concrete composed of natural chert coarse aggregate having a maximum size of 1-1/2 in. Commonly, the coarse aggregate particles are less than 1 in. maximum size. The fine aggregate was a natural sand common to these two samples as well as the limestone concrete samples (940008 and 940009).

8. Samples 940008 and 940009 consisted of concrete composed of crushed limestone coarse aggregate with a maximum size of 1 in.

9. Examination of the slab cross sections revealed cracking below the exposed concrete surface. Some incipient flaws in the aggregate could be seen in the aggregate particles. These were recognized by their alignment with structural features in the particle and their discoloration due to weathering. Many of the fractures in the aggregate caused by the removal technique could be traced to the action of the cutting teeth. Fractures could be correlated with the grooves generated by the removal tool.

10. Specimen 930245 sustained damage to an average depth of 0.25 in. Some shattered particles were observed on the exposed concrete surface. The shattered particles tended to produce loose debris at the surface, but it was not extensive. Some cracking parallel to the surface was noted.

11. Cracking in specimen 930246 tended to be normal to the surface in the aggregate particles (Figure C1) and parallel to the surface in the paste portion of the concrete (Figures C2 and C3). The damaged concrete was limited to approximately 1-in. depth. Cracked aggregate particles were fractured to the entire depth of the particles.

Fractures in the paste were often associated with the interfaces between the aggregate and the paste and the continuation of that separation into the adjacent paste. Cracking in the paste was limited to approximately 1 in. or the depth associated with the aggregate particles with which it was in contact.

12. Specimens 940008 and 940009 consisted of dark gray fine grained limestone aggregate, and the removal device scratched through these particles and crushed them into a light gray powder which was easily removed. The cutting tool left a groove in the limestone aggregate concrete similar to that observed in the chert aggregate concrete. In the grooved and crushed zones, coarse aggregate particles were also highly fractured and easily dislodged (Figure C4).

13. Depth of fracturing in the aggregate was limited to full depth of a coarse aggregate particle (approximately 1 in.). The fractures in the paste were associated with the fracturing in the coarse aggregate particles (Figures C5 and C6). Cracks in the limestone were random, with the cracks subparallel to the surface continuing into the paste in many cases (Figure C7). There were also cracks developing along the aggregate-paste interface that continued into the paste.

14. Results of this investigation indicate the following:

a. Damage on the surface was easily observed and appeared as loose debris or where the material was crushed. Reflectance of the powder made the material appear lighter in color.

b. There was damage to the concrete beyond the surface region of the concrete. Most of the damage was associated with the coarse aggregate particles, but some was found in the paste as cracks parallel to the surface.

c. Damage appeared to be limited to approximately a 1-in. depth.

d. Damage was most severe nearer the surface and lessened deeper into the concrete.

e. The depth of damage may be associated with the maximum size of the coarse aggregate. The larger the coarse aggregate the deeper the potential for damage.

f. Problems may be encountered with bonding of new concrete to these surfaces without additional surface preparation.

4 Encls
Figures C1-C7

G. SAM WONG
Petrography and Chemistry Group
ESB/CTD/SL

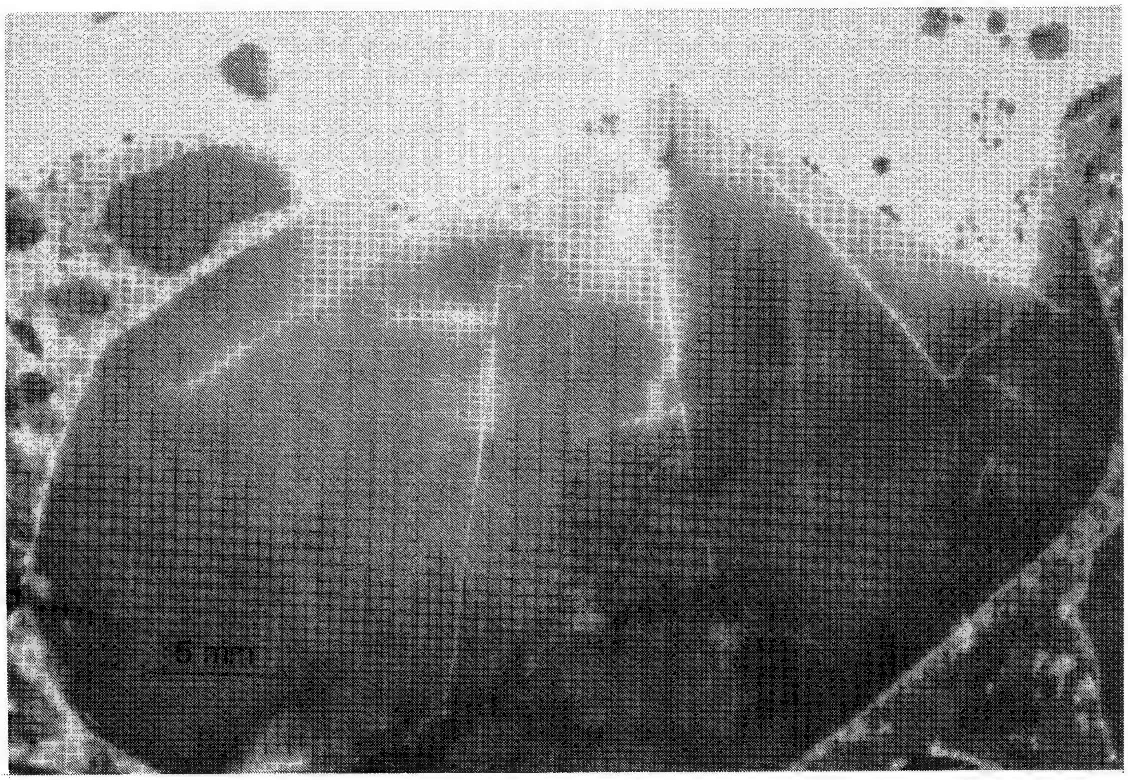

Figure C1. Specimen 930246 consisted of rounded chert coarse aggregate particles. This is a cross-sectional view of the concrete at the surface showing radial cracks from central location impacted by the removal apparatus. Loose debris can also be observed. Also seen at the bottom of the micrograph are some incipient dendritic cracks bordered by darker areas. 4X

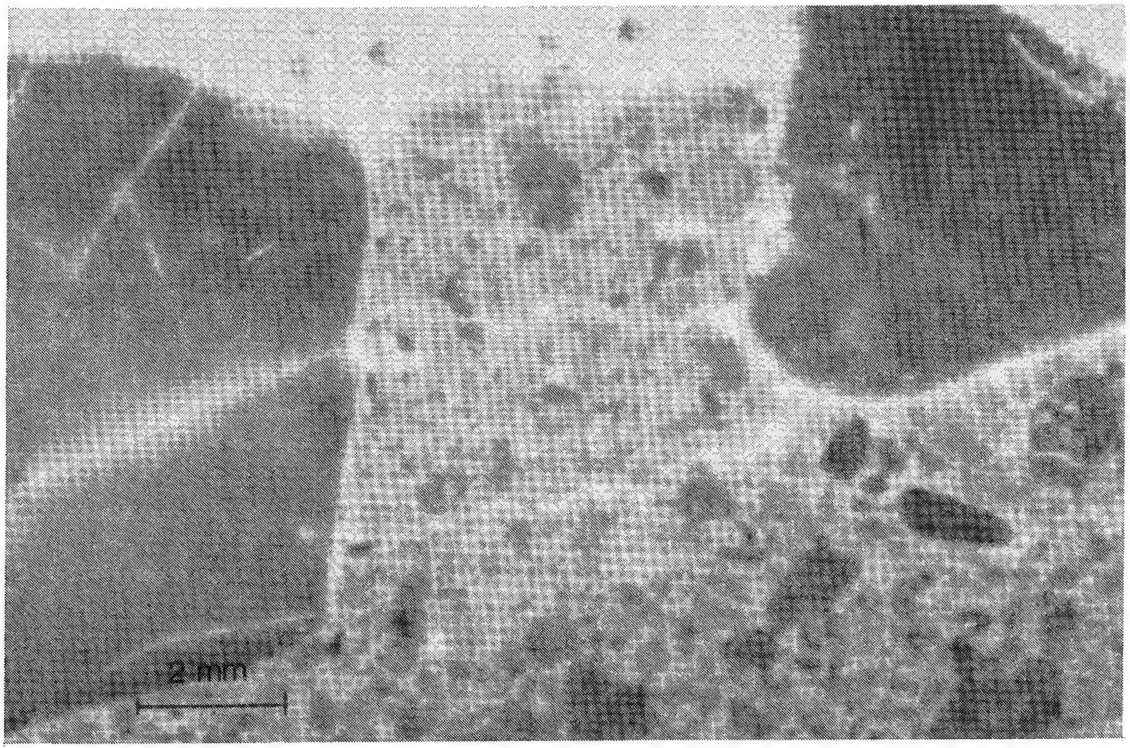

Figure C2. Specimen 930246. Micrograph of cross-sectional view of surface showing cracks in the aggregate extending into the paste. The aggregate particle in the left portion of micrograph is fractured, while the smaller particle in the right portion of micrograph remains intact. However, the aggregate particle in the right is showing tendency of separation along the aggregate-paste interface. 10X

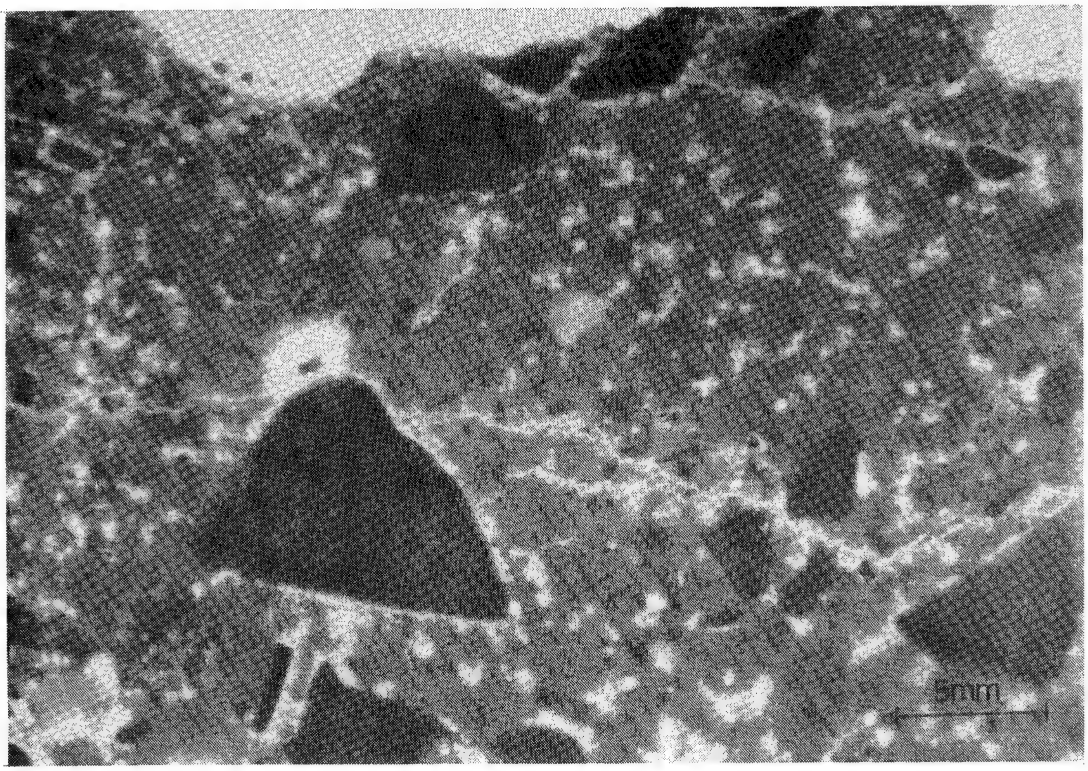

Figure C3. Specimen 930246. Fracturing of smaller aggregates is evident in the upper center of micrograph. 4X

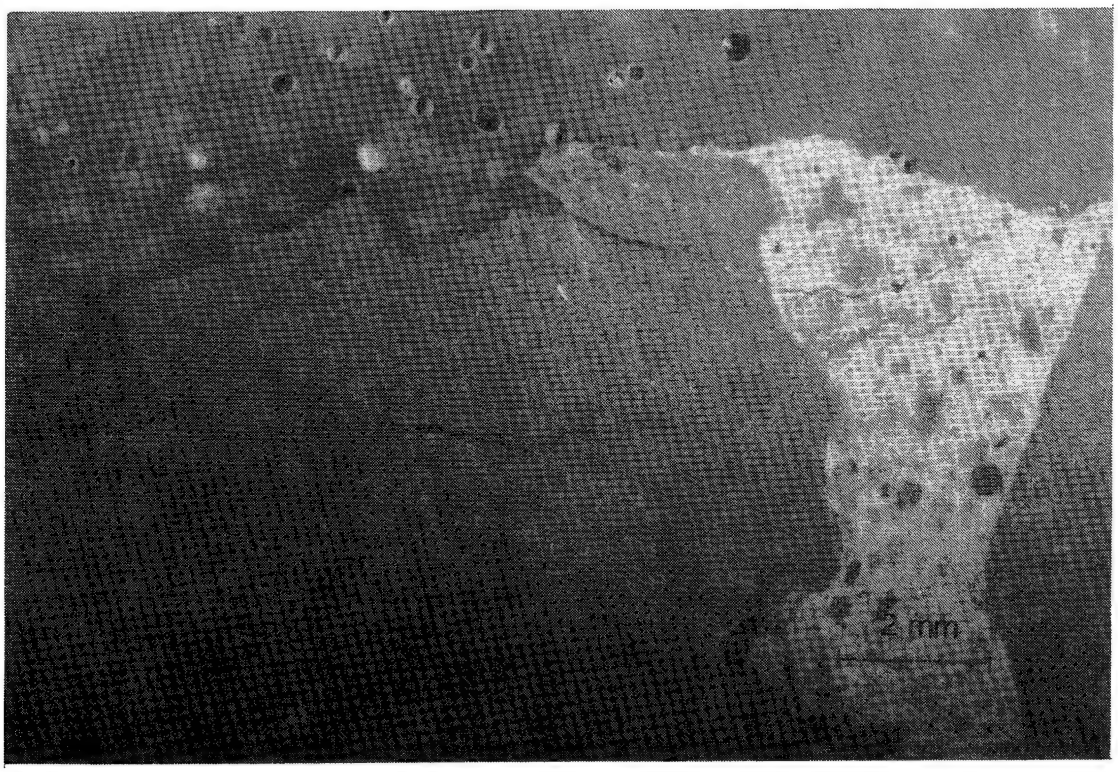

Figure C4. Specimen 940008. Cross-sectional view of surface concrete showing interlocking fractured pieces of aggregate and pieces of paste that may easily be dislodged mechanically. 10X

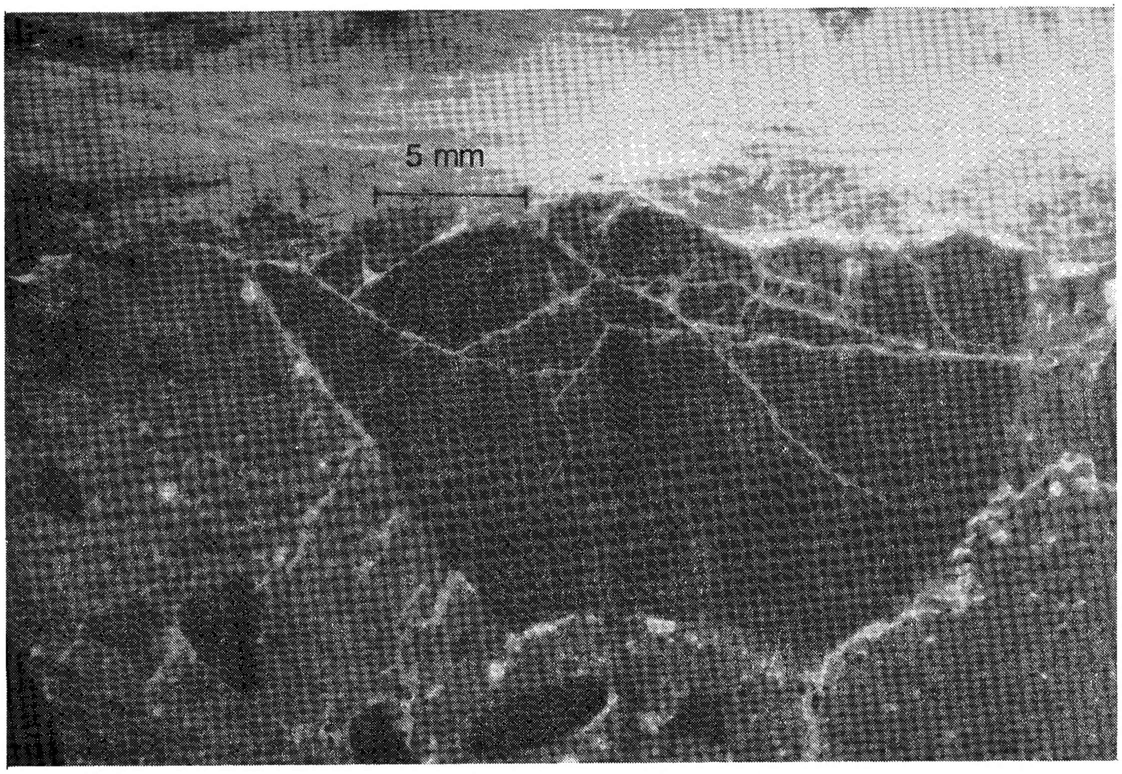

Figure C5. Specimen 940008. The concrete is made with limestone coarse aggregate. The cross-sectional view of the surface shows a fractured coarse aggregate particle. The fracture density is highest near the surface and declines deeper in the concrete. Fractures extend from the aggregate into the paste in many instances. 4X

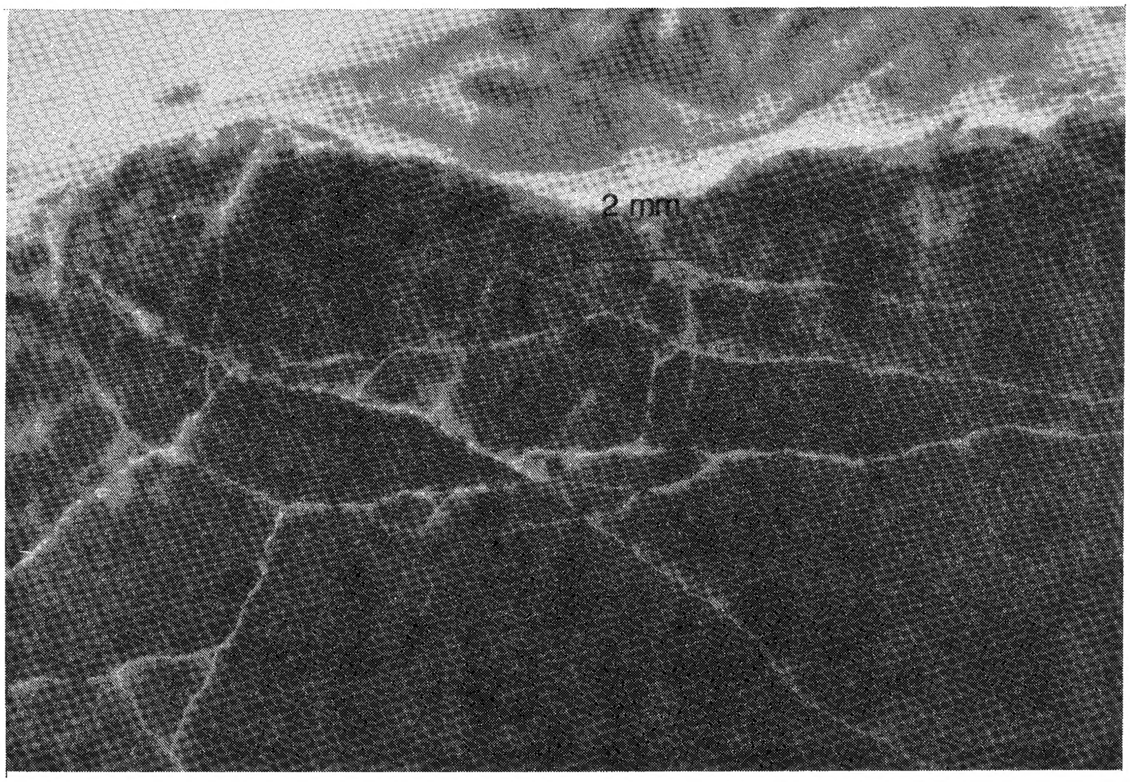

Figure C6. Specimen 940009. Cross-sectional view showing severe fracturing of limestone coarse aggregate particle near the top surface of the specimen. 11X

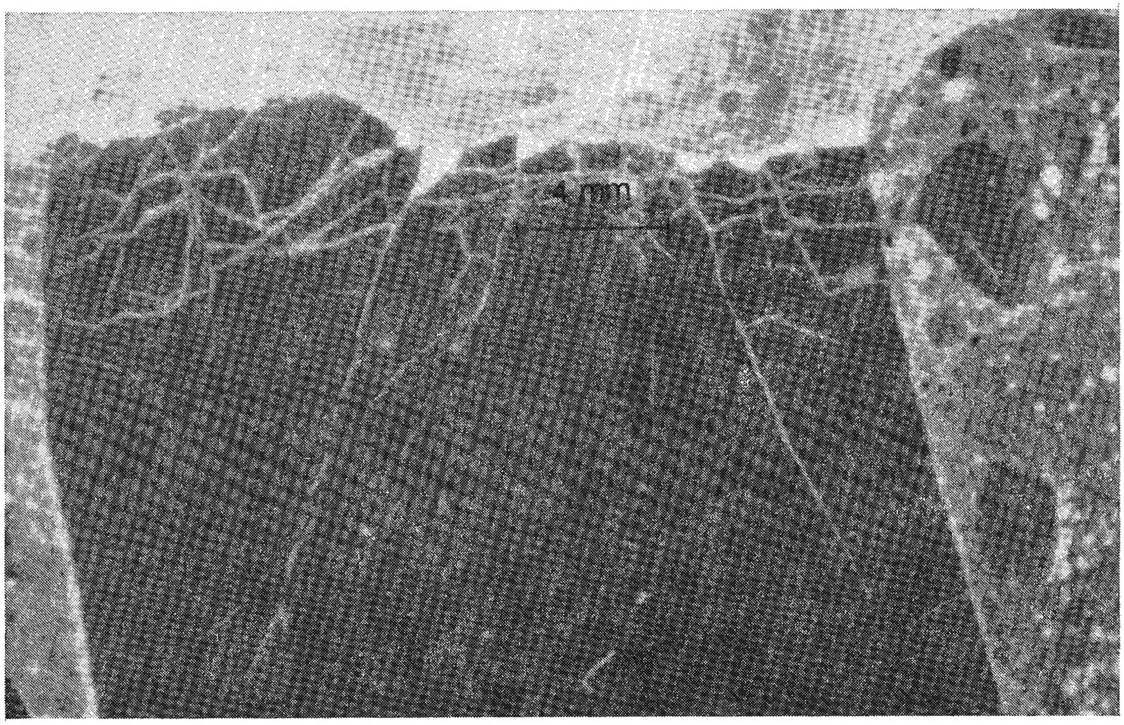

Figure C7. Specimen 940009. Cross-sectional view of surface concrete showing fracturing of coarse limestone aggregate particles. Some of the fracturing in the aggregate particle extends into the paste. 5X

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13. ABSTRACT *(Maximum 200 words)*

The objectives of the research described in this report were to quantitatively demonstrate the diamond-coated-bit, cutter-boom head tool as an expedient, cost-effective concrete removal method for the rehabilitation of locks, dams, tunnels, and other similar structures and to provide real production and cost data for comparison with other removal methods. The results of the testing indicate that diamond-coated bits do not remove concrete any faster than conventional tungsten-carbide bits. The diamond-coated bit inserts appeared to wear less than the tungsten-carbide inserts but showed signs of impact damage. The estimated benefit of the diamond-coated bits having more than 10 times longer life than that of conventional bits could not be proved or disproved as testing was discontinued because of the excessive wear of bit shanks. The results of petrographic analysis showed that the impact of cutter bits induces microcracking in the concrete surfaces that remain after removal.

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